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Search for third-generation leptoquarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We report on a search for charge-1/3 third-generation leptoquarks (LQ) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the D0 detector at Fermilab. Third generation leptoquarks are assumed to be produced in pairs and to decay to a tau neutrino and a b quark with branching fraction B. We place upper limits on $\sigma(p\bar{p} \to LQ\overline{LQ}) \times B^2$ as a function of the leptoquark mass M_{LQ}. Assuming $B = 1$, we exclude at the 95% confidence level third-generation scalar leptoquarks with $M_{LQ} < 229$ GeV.

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Leptoquarks (LQ) are bosons predicted in many extensions of the standard model (SM) [1]. They carry both nonzero lepton and color quantum numbers and decay to a lepton and quark (or antiquark). To satisfy experimental limits on lepton number violation, on flavor-changing neutral currents, and on proton decay, leptoquarks of mass accessible to current collider experiments are constrained to couple to only one generation of leptons and quarks [2]. Therefore, only leptoquarks that couple within a single generation are considered here.

This Letter reports the results of a search for charge-1/3 third-generation leptoquarks produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We assume that leptoquarks are produced in pairs by $q\bar{q}$ annihilation or gg fusion, i.e., $p + \bar{p} \rightarrow LQ + \overline{LQ} + X$. These processes are independent of the unknown leptoquark-lepton-quark coupling, and the pair production cross section has been calculated including next-to-leading order terms for scalar leptoquarks [3]. Such leptoquarks would decay into either a ν_τ plus a b quark or a τ lepton plus a t quark. We search for the decay signature where both leptoquarks decay via $LQ \rightarrow \nu_\tau + b$ with branching fraction B, resulting in a $\nu_\tau \bar{\nu}_\tau b\bar{b}$ final state. Upper limits on the cross section times B^2 as a function of leptoquark mass (M_{LQ}) are measured and then used to determine lower limits on M_{LQ} assuming they are scalar for which the calculated cross section is lower and better determined than that for vector leptoquarks which have only been calculated to leading order [4]. Previous limits from Fermilab Run I data were reported by both the D0 [5] and CDF [6, 7] collaborations based on significantly smaller integrated luminosities and at a slightly lower center-of-mass energy compared with the Run II data available now.

The upgraded Run II D0 detector [8] consists of layered systems surrounding the interaction point. Closest to the beam are the silicon microstrip tracker and a central fiber tracker, both immersed in the field of a 2 T solenoid. These measure the momenta of charged particles and reconstruct primary and secondary vertices. Jets and electrons are reconstructed using the pattern of energy deposited in three uranium/liquid-argon calorimeters outside the tracking system with a central section covering $|\eta| < 1.1$ and two end calorimeters housed in separate cryostats covering the regions up to $|\eta| \approx 4$ (where $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity, and θ is the polar angle with respect to the proton beam direction). Jet reconstruction uses a cone algorithm [9] with radius $\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ in pseudorapidity and azimuthal angle (ϕ) space about the jet's axis. The jet energy scale was calibrated using the transverse energy balance in photon-plus-jet events [10]. A muon system outside the calorimeters consists of a layer of drift tubes and scintillation counters before 1.8 T iron toroids and two similar layers outside the toroids. Identified muons were required to have hits in both the wire chambers and scintillation counters and were matched to a central track which determined their momenta. The missing transverse energy, $\not{E}_T$, was determined by the vector sum of the transverse components of the energy deposited in the calorimeter and the p_T of detected muons.

Data collection used a three level trigger system and two trigger selections were analyzed for the results presented here. The first, called the missing energy trigger here, used missing energy plus jets elements. At Level 1 it required at least three calorimeter trigger towers with $E_T > 5$ GeV, where a trigger tower spans $\Delta\phi \times \Delta\eta = 0.2 \times 0.2$. The vector sum of all jets' transverse momenta, defined as $\not{H}_T \equiv |\sum_{\rm jets} \vec{p_t}|$, was required to be greater than 20 GeV at Level 2 and greater than 30 GeV at Level 3. For 16% of the integrated luminosity, the acoplanarity, defined as the azimuthal angle between the two leading jets, was required to be less than 169° and the $H_T \equiv \sum_{\rm jets} |\vec{p_t}|$ be greater than 50 GeV. An integrated luminosity of 360 pb^{-1} [11] was collected with this trigger. The second trigger, called the muon trigger here, used muon and jet elements to increase the acceptance for events where one of the b jets was identified by its associated muon. At Level 1 it required at least one muon candidate and at least one calorimeter trigger tower with $E_T > 3$ GeV. Higher jet thresholds were imposed at Level 2 and finally 25 GeV at Level 3. An integrated luminosity of 425 pb^{-1} was collected with the muon trigger. These missing energy and muon triggers were not independent and only the 65 pb^{-1} of the muon trigger data sample which does not overlap was used for the combined result.

Signal samples for leptoquark masses between 150 and 400 GeV were generated with PYTHIA 6.202 [12]. Instrumental background comes mostly from QCD multijet processes with false $\not{E}_T$ arising from mismeasurement, and dominates the low $\not{E}_T$ region. Physics backgrounds are SM processes with real $\not{E}_T$ and were estimated from Monte Carlo (MC) simulations. The most important are leptonic decays of W/Z bosons plus jets with $Z \rightarrow \nu\bar{\nu}$ or when a lepton remains unidentified or is misidentified as a hadron, and processes which produce top quarks. For all MC samples except $t\bar{t}$ and single top quark, the next-to-leading order cross sections were obtained from Ref. [13]. Cross sections for $t\bar{t}$ and single top quark production were taken from Ref. [14] and [15], respectively. At the parton level, single top quark MC events were generated with COMPHEP 4.4 [16], and ALPGEN [17] was used for all other samples. These events were then processed with PYTHIA which performed showering and hadronization. An average of 0.8 minimum bias events was superimposed on each MC event to match the number of

TABLE I: Predicted numbers of signal and background events before b tagging and after all requirements (statistical errors only).

Data sample	Missing energy trigger 360 pb^{-1}		Muon trigger 425 pb^{-1}	
Process	Pretag requirements	All requirements	Pretag requirements	All requirements
$W \rightarrow \mu\nu + jj$	108 ± 6	0.28 ± 0.11	100 ± 7	0.06 ± 0.06
$W \rightarrow e\nu + jj$	160 ± 14	0.02 ± 0.01	6 ± 3	0
$W \rightarrow \tau\nu + jj$	396 ± 36	0.17 ± 0.05	7 ± 5	0
$Z \rightarrow \nu\bar{\nu} + jj$	603 ± 18	0.45 ± 0.16	25 ± 4	0
$t\bar{t}$ and single top	36 ± 1	1.42 ± 0.11	18 ± 0.6	0.80 ± 0.11
$W/Z + c\bar{c}$	18 ± 1	0.46 ± 0.11	3.01 ± 0.49	0.21 ± 0.12
$Z + b\bar{b}$	6 ± 1	0.67 ± 0.08	1.89 ± 0.20	0.22 ± 0.06
$W + b\bar{b}$	8 ± 1	0.59 ± 0.11	4.43 ± 0.38	0.41 ± 0.11
Total SM expected	1335 ± 43	4.1 ± 0.3	165 ± 10	1.7 ± 0.2
QCD contribution	40 ± 40	< 0.1	6 ± 6	< 0.2
Data	1241	1	146	0
Signal $M_{LQ} = 200$ GeV	34 ± 1	10.1 ± 0.3	9.6 ± 0.4	3.8 ± 0.2
Signal acceptance	35.9%	10.4%	8.4%	3.3%

additional collisions observed in data. The resulting samples were processed using a full GEANT simulation of the D0 detector [18]. CTEQ5L [19] was used as the parton density function in all cases.

For both data samples, a set of preselection requirements was applied prior to b tagging in order to reduce the number of events from QCD multijet and W/Z+jets processes. Values for preselection cuts and jet quality criteria were driven by trigger requirements. To reject $W \rightarrow \ell\nu$ decays, a veto was applied to events with isolated electrons or muons with $p_T > 5$ GeV. Likewise, events containing a track with tighter isolation cuts and with $p_T > 5$ GeV were rejected to reduce the contribution of leptons which remained unidentified. The number of events with mismeasured $\not\!\!E_T$ was reduced by requiring that the primary vertex be within ± 60 cm in the beam direction from the center of the detector and by eliminating those where the $\not\!\!E_T$ direction and a jet overlapped in ϕ. For the missing energy trigger sample, events were required to have $\not\!\!E_T > 70$ GeV, the leading jet was required to have $|\eta| < 1.5$ and $p_T > 40$ GeV, and, for events without muons, scalar $H_T > 110$ GeV. For the muon triggered sample, the preselection required a muon with $p_T > 4$ GeV and a leading jet with $|\eta| < 1.5$ and $p_T > 40$ GeV (> 50 GeV if not associated with a muon). Additional requirements were a second jet with $p_T > 20$ GeV, $\not\!\!H_T > 50$ GeV and $\not\!\!E_T > 70$ GeV. The numbers of pre-selected events in both samples and their estimated sources are given in Table I.

Figure 1 shows distributions of $\not\!\!E_T$ and H_T with the signal LQ and background SM events normalized to the total integrated luminosity. The data samples reproduce the SM expectations for $\not\!\!E_T > 90$ GeV indicating that contributions from QCD multijet processes are small in this range. The contribution from these events is estimated from the $\not\!\!E_T$ distribution below 70 GeV by a fit to an exponential after subtracting SM contributions. This is similar to the technique used in our search for scalar bottom quarks [20] and total, for $\not\!\!E_T > 70$ GeV, 40 ± 40 events and 6 ± 6 events in the missing energy and muon trigger samples, respectively. After b tagging, which is described below, the contributions from this source are less than 0.1 and 0.2 events respectively, and a value of 0 events was conservatively used for limit calculations.

Backgrounds with light flavor jets were reduced by requiring the presence of b-tagged jets. We used jets that

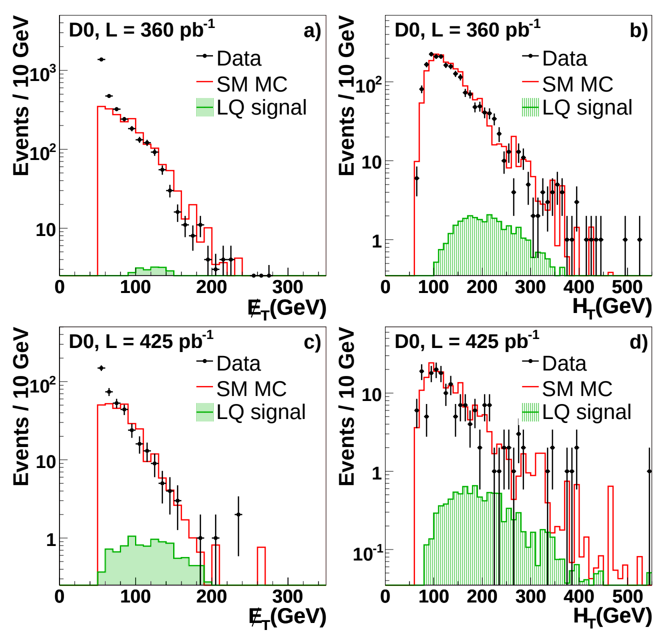

FIG. 1: The $\not\!\!E_T$ distributions and the scalar H_T (with $\not\!\!E_T > 70$ GeV) distributions before b tagging for data (points) compared to SM background (solid histogram). The missing energy trigger sample is given in (a) and (b) and the muon trigger sample in (c) and (d). The shaded histograms are the expected contribution for a 200 GeV LQ signal.

TABLE II: Numbers of observed and predicted events after final selection, the effective signal acceptance (with total error), and the observed and expected 95% C.L. cross section limits as a function of M_{LQ}. Scalar cross sections were used to calculate the expected numbers of signal events.

M_{LQ} GeV	($\not\!\!E_T$, H_T)[a] GeV	Data events	SM ± stat ± sys events	Signal ± stat ± sys events	Effective acceptance (%)	σ 95% C.L. limit obs./exp. (pb)
170	(70,110)	4	7.3 ± 0.4 ± 1.7	27.0 ± 0.6 ± 4.6	10.4 ± 1.5	0.163/0.232
200	(90,150)	1	4.3 ± 0.3 ± 1.0	10.7 ± 0.3 ± 1.7	11.1 ± 1.6	0.101/0.163
220	(90,190)	1	3.3 ± 0.3 ± 0.7	5.8 ± 0.2 ± 0.9	11.5 ± 1.6	0.097/0.142
240	(90,190)	1	3.3 ± 0.3 ± 0.7	3.7 ± 0.1 ± 0.6	13.6 ± 2.0	0.081/0.119
280	(90,190)	1	3.3 ± 0.3 ± 0.7	1.3 ± 0.0 ± 0.2	15.5 ± 2.2	0.071/0.105
320	(90,190)	1	3.3 ± 0.3 ± 0.7	—	17.5 ± 2.5	0.063/0.092
360	(90,190)	1	3.3 ± 0.3 ± 0.7	—	18.9 ± 2.7	0.058/0.085
400	(90,190)	1	3.3 ± 0.3 ± 0.7	—	21.6 ± 3.1	0.051/0.074

[a] $\not\!\!E_T > 70$ GeV, $H_T > 140$ GeV applied to all muon-tagged events.

contained either tracks with a significant impact parameter or muons to select b-jet candidates. Events were required to have two b tags with at least one passing the impact parameter criterion. For events selected with the muon trigger, a b jet tagged using a reconstructed muon in proximity to a jet was required. Otherwise, the events from both trigger samples were treated in an identical way for the remainder of the analysis.

We assigned a b probability to a jet based on properties such as the existence of tracks with a significant impact paramater that indicated the presence of a secondary vertex. The algorithm [21] required at least two tracks in a jet, each with a hit in the silicon tracker. Tagging probabilities in simulated jets used parameterizations derived from data. The probability of a jet to be of light flavor was derived and required to be less than 2%, which yielded a b-tag efficiency of about 45% per b jet. This choice maximized the expected LQ mass limits after all other cuts were applied.

Muon-tagged jets were also considered b-jet candidates. Muon thresholds were raised to $p_T^\mu > 6$ GeV to suppress contributions from π/K decays. Remaining backgrounds from W boson decays to muons were due to accidental overlap of a muon with a nearby jet. We required that the sum of track p_T in a cone of 0.5 around the muon be greater than 10 GeV, and that the approximate p_T of the muon relative to the jet's axis, $\Delta\mathcal{R}_{\mu-\mathrm{jet}} \times p_T^\mu$, be less than 3.5 GeV, as muons originating from jets are closer to the jet axis for higher values of p_T [22]. These requirements are not independent and combining them was found to reduce the W boson background by 95% while keeping 77% of the signal. Muon tagging has a b-tag efficiency of about 11% with less than 0.5% of light flavored jets passing the tag criteria.

Since signal events are dominated by high energy b jets, the quantity $X_{jj} \equiv (p_T^{\mathrm{tag1}} + p_T^{\mathrm{tag2}})/(\Sigma_{\mathrm{jets}} p_T)$ was defined, with the muon p_T included in the p_T of the tagged jet, where applicable. We required $X_{jj} > 0.8$ which was found to significantly reduce the contribution from top quark pair events. Since $\not\!\!E_T$ and H_T increase for higher values of M_{LQ}, we optimized the requirements on these parameters as a function of leptoquark mass by maximizing $S/\sqrt{B}$, where S and B are estimated signal and background rates. The values used for the minimum H_T and $\not\!\!E_T$ are given in Table II and were applied only to the double b vertex tagged sample. For the muon-tagged events, the $H_T > 140$ GeV requirement was applied, and the $\not\!\!E_T$ cut remained at 70 GeV as these events have a smaller contribution from light flavor jets.

Results of the final event selection along with predicted numbers for signal ($M_{LQ} = 200$ GeV) and SM backgrounds are listed in Table I. The latter originate mostly from $W/Z + b\bar{b}$ production and top quark events.

Sources of systematic uncertainties include errors in the determination of the integrated luminosity (6.1%) [11] and SM cross sections (15%). Trigger and jet selection efficiencies were measured with data and their contribution to the systematic errors is small. Jet energies and $\not\!\!E_T$ were varied within the energy scale correction uncertainty, and the impact on signal acceptance and background rates was determined with MC to be 3% and 10% respectively. Jet b-tagging efficiency uncertainties are 12% for signal and 11% for background.

One event remains in the combined data sample for the selection criteria used for all points with $M_{LQ} \geq 200$ GeV. This is consistent with the $3.3 \pm 0.3 \pm 0.7$ expected events from SM processes. The probability of the observed deficit is 16%. The 95% C.L. upper limits on the $\sigma(p\bar{p} \to LQ\overline{LQ} \to \nu\bar{\nu}b\bar{b}) \times B^2$ were obtained using the techniques in Ref. [23]. The effective signal acceptances of the combined sample (normalized to 360 pb^{-1}), numbers of events, and the resulting limits as functions of M_{LQ} are summarized in Table II.

Figure 2 shows the cross section limit as a function of M_{LQ}. Limits on the scalar leptoquark mass were obtained by the intersections of the observed 95% C.L. cross section limits with the lower bounds of a next-to-leading order calculation for which variation of the renormalization scale μ from $0.5M_{LQ}$ to $2M_{LQ}$ and the PDF uncertainties [24] were included. If $B(LQ \to \nu_\tau b) = 1$ is

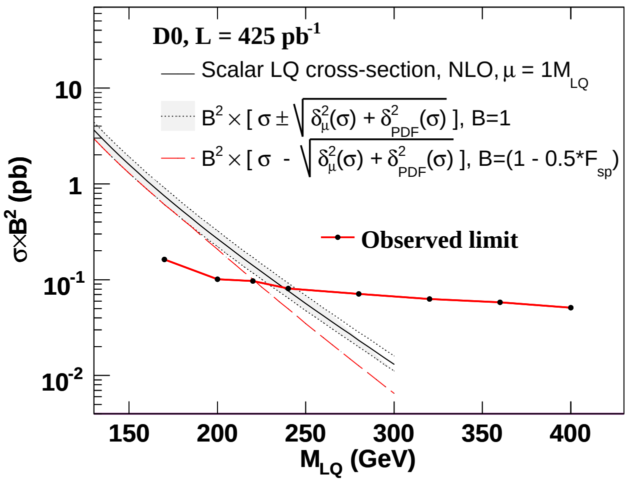

FIG. 2: The 95% C.L. limit on $\sigma \times B^2$ (points plus solid line) as a function of M_{LQ}. The prediction for scalar leptoquarks (solid line) include an error range (in grey) of μ between $0.5M_{LQ}$ and $2M_{LQ}$. The long-dashed line below the theory band indicates the threshold effect for the τt channel.

assumed, our limit is $M_{LQ} > 229$ GeV. We can also consider the case where $LQ \rightarrow t\tau$ decays occur. If we assume that the leptoquark couplings to $\nu_\tau b$ and $t\tau$ are the same, the branching fraction for $LQ \rightarrow \nu_\tau b$ is then $1 - 0.5 \times F_{sp}$ where F_{sp} is the phase space suppression factor for the $t\tau$ channel [25]. This is shown on the figure as a displacement from the lower edge of the theory band. With this assumption, the 95% C.L. lower mass limit for scalar leptoquarks is 221 GeV.

In conclusion, we observe one event with the topology $b\bar{b} + \not\!\!E_T$ consistent with that expected from top quark and W and Z boson production and set limits on the cross section times branching fraction squared to the $b\nu$ final state as a function of leptoquark mass for charge-1/3 leptoquarks. These limits are interpreted as mass limits for third-generation scalar leptoquarks and increase the excluded value by 81 GeV compared to previous results.

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tion).